IGNITION-DEPENDENT BEHAVIOR OF BLACK POWDER MODEL ROCKET ENGINES

by Arthur H. Barber III
NAR 4322

5 May, 1978

ABSTRACT

IGNITION-DEPENDENT BEHAVIOR OF BLACK-POWDER MODEL ROCKET ENGINES

by Arthur H. Barber
NAR 4322

This project had two related objectives: to measure the effects of various standard ignition methods on the performance characteristics of black-powder model rocket engines, and to measure the delay between booster engine cutoff and second-stage ignition in multi-staged models. To achieve these objectives, over 200 model rocket engines from the same manufacturer's batch were static tested: 105 cored type (B14-0), and 100 cored-end-burning type (A8-0). These were generously donated by Ed Brown and Dane Boles of Estes Industries.

For the ignition tests the standard igniters produced by Estes, Centuri, AVI, and FSI, along with plain nichrome wire and electric matches, were tested five times in each type of engine. It was determined that for cored engines, the AVI igniter produced a peak thrust about 10% higher than most other types, and slightly more total impulse. The Centuri Sure-Shot reduced peak thrust by about 10%, and the electric match took 0.01 seconds longer to fire the engine and produced a slightly reduced total impulse, while having no effect on thrust level. All other igniters produced virtually identical results in cored engines. For cored-end-burners, performance was independent of the ignition system used.

The staging delay tests indicated that none of the three staging methods used (engines connected by a tape collar, engines touching but not connected, and engines separated by 3" of body tube) had any effect on the time delay between bottom engine separation and top engine ignition. The only factor which significantly affected this delay was the size of the upper engine nozzle: the larger it was, the smaller the delay. The delay averaged 0.13 seconds when the top engine was an A8- (0.12" nozzle), and 0.05 seconds when it was a B14- (0.17" nozzle), regardless of the booster engine used.

A series of tests on tandem engines indicated that the thrust and impulse of the second engine are altered in a significant and complex manner, but that the inter-engine staging delay is less than for conventionally-staged engines. It averaged 0.07 seconds for B14-to-B14 tandems, and 0.03 seconds for B14-to-A8 and A8-to-A8 tandems.

The results of this project indicate that the igniter used to fire a small black-powder model rocket engine can have a small effect on its subsequent performance if it is a cored type, but no effect if it is a cored-end-burning type. The results also indicate that all commonly-used staging systems are equally effective in obtaining rapid ignition of the upper-stage engine. The interstage ignition delays measured in these tests may be of value to rocketeers attempting to do extremely accurate altitude prediction calculations, as they will lead to altitudes somewhat different from those produced by the currently accepted assumption that there is zero staging delay.

INTRODUCTION

There has always been considerable debate within the hobby of model rocketry over which manufacturer's brand of igniter is the best for contest use. The two factors generally discussed in this debate are the device's reliability, and its effects on the ballistic characteristics of the engine in which it is used. Reliability is a difficult quantity to measure; this project has settled for simply trying to accurately measure the effects of different igniters on the peak thrust and rate of thrust buildup of a typical cored-type engine (the Estes B14-0), and of a typical cored-end-burning type engine (the Estes A8-0). A very large number of these engines, all from the same batch, were tested in order to give statistical validity to the conclusions. An effort was made to test each of the many general types of igniter currently available.

A second, closely-related topic of concern which this project looked into was the dynamics of the staging process, particularly the time delay between blow-through (and separation) of the lower-stage engine and the ignition of the upper stage engine. Current practice is to assume that this is zero; if it is, in fact, non-zero this could have some impact on the accuracy of current altitude prediction efforts.

APPARATUS AND PROCEDURE

The basic piece of apparatus used in this project was a system to measure the variation of model rocket engine thrust with time. The sensor component of this system was a 1"x7" rectangular cantilever beam, made of 1/8" mild steel. To the end of this was welded a steel tube just large enough to accept 18mm diameter model rocket engines. The opposite end was rigidly clamped to a steel I-beam. Deflection of the beam (which was proportional to engine thrust) was measured by four SR-4 strain gauges (gauge factor 2.05, resistance 120 ohms), wired in a Wheatstone Bridge arrangement and centered 4.75" from the center of the motor tube. Just below the motor tube was attached an aluminum plate, which was submerged in a viscous oil (STP) to a depth of several inches to give the system a slightly-less-than-critical (0.6) damping ratio. The whole system had a natural frequency of approximately 50 cycles per second, and a response time of 0.013 seconds (for 91% response to a square-wave input). All data in this project were obtained by analysis of the thrust-vs-time graphs produced by this device when connected to a Sanborn Twin-Viso chart recorder.

The ballistic variations expected in this project's tests were very small, quite likely smaller than the variations which previous experience indicated could be expected between two different batches of the same engine. It was therefore essential to the validity of this project's results that all of the engines of each particular type be from the same manufacturer's batch. Ed Brown and Dane Boles of Estes Industries donated over 100 A8-0 and 100 B14-0 engines from the same batch to solve this difficulty. Because of this, it could be expected that major differences between test series results would be

due only to differences in the effects of igniters or staging methods, and not to batch variations.

For the igniter tests, seven different types were tried: the Estes igniter (nichrome wire with the center 1" evenly coated with a low-flash-point compound) held in by a tissue ball, the Estes igniter held in with tape, the Centuri Sure-Shot igniter (a piece of fuse ignited by a nichrome wire), the AVI igniter (nichrome wire with a small ball of low-flash-point compound in the center), the FSI igniter (a fuse wrapped along its whole length with nichrome wire), plain nichrome wire, and the "electric match", an Atlas Chemical Industries ignition squib that produces a hot jet of gas when ignited. The AVI, FSI, and plain nichrome igniters were held in the nozzle by a ball of tissue; the electric match and Sure-Shot igniters were held in with tape. All of the tissue balls used were of the same size, and were rammed the same distance into the nozzle with the same tool. All seven of these igniters were used on the cored-type (B14-) engines. The electric match was far too large to fit into the A8-size nozzle, however, so it was not used for the cored-end-burning engine ignition tests. Igniters of this type are never commonly used on any but cored-type engines. All tests were done at the same ambient temperature, as previous work by this investigator had indicated that this variable could have significant effect on ballistic characteristics.

Three commonly used multi-staging techniques were tested in the effort to measure interstaging delays, and a series of tests were also performed on "tandem" engines (two engines epoxied end-to-end so that the second one fires through the burned-out casing of the first). In all of the staging tests, the junction between the two engines was enclosed by a slip-fit piece of 19mm body tube, lightly taped to

the first engine so that it is pulled free when this engine is kicked off at staging. In the first series of staging tests, a single-thickness tape collar was wrapped around the engine-to-engine junction inside the body tube, a procedure common since the publication of Estes Industries TR-2 on multistaging. It is well-known that this technique substantially increases the probability of the top engine being successfully ignited, but its effect on the speed of this ignition was unknown. For the second series of tests, the two engines were placed end-to-end in the body tube sleeve as before, but without the tape collar. This is known to be less reliable than the first method. The final series of staging tests used a long section of coupling 19mm body tube to achieve a separation of 3" from the end of the casing of the first engine to the front of the top engine casing. This is used in some sport models and many multi-stage scale designs. Figure 1 below illustrates this configuration and the set-up of the test apparatus.

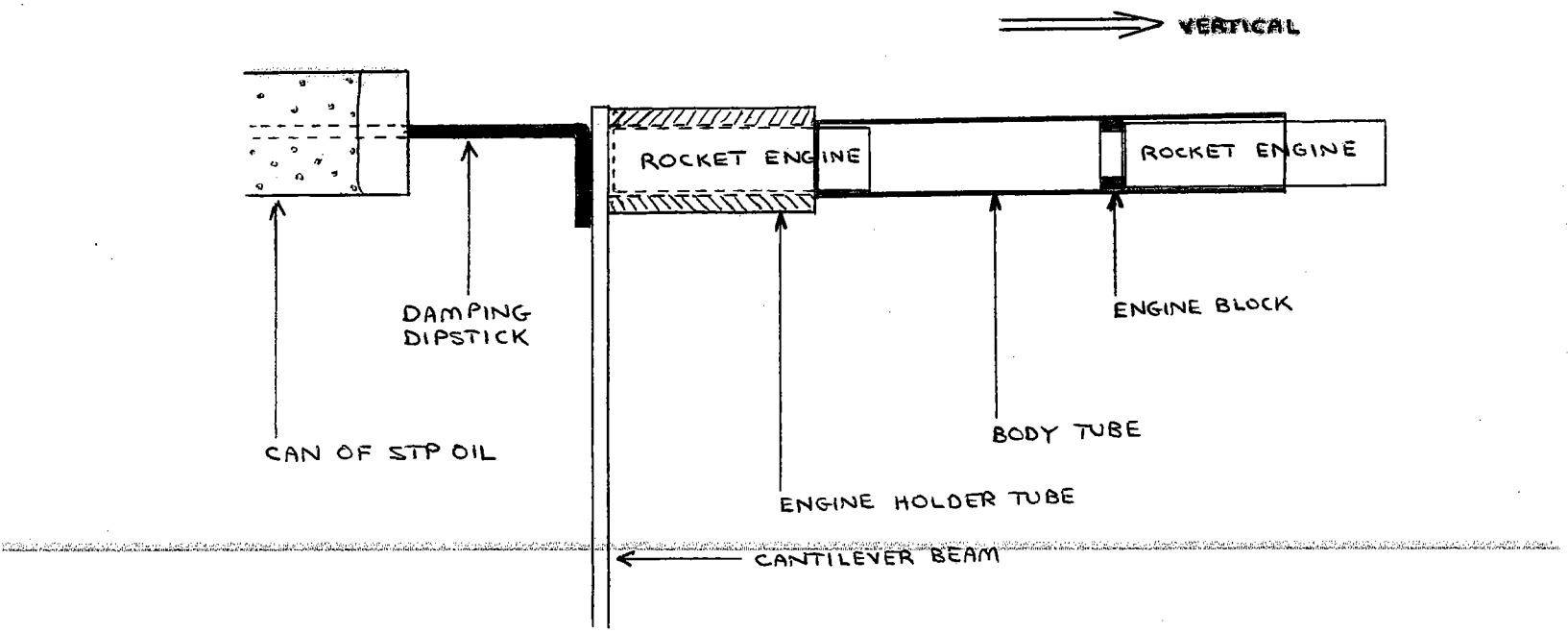


FIGURE 1. Setup of thrust stand for staging tests.

Prior to each series of tests, the test stand was calibrated for thrust measurement by piling on assorted weights in one-pound increments, up to the expected peak thrust of the engines being tested. These weights were centered on the engine-holding tube.

It was considered quite likely that either the chamber pressure of the first engine at the time of its burnthrough, or the size of the nozzle of the second engine, could be factors affecting the delay time (if any) between staging. To examine this, each staging method was tested on several different engine permutations, with five tests being done on each arrangement. For every staging method, and for the tandem engine tests, the permutations tested were B14-to-B14, A8-to-A8, and B14-to-A8. Comparison of the two series with B14 lower engines should indicate if the choice of upper engine had any effect, and comparison of the series' with A8 upper engines should show the effect of lower engine choice. In the tests of staging with a 3" separation, A8-to-B14 tests were done by mistake instead of A8-to-A8, but both of the necessary comparisons could still be made. Results obtained from tests of the A8- are considered to be applicable to virtually all other 18mm cored-end-burning engines because of their similarity of grain core design and nozzle size.

DATA

The raw data obtained from this project's experiments consisted of a prodigious number of chart-recorder graphs of engine thrusts versus time. A representative selection of these is presented in Appendix 1; there were 135 in all. Each of these was analyzed to obtain certain selected performance figures, which are presented in tabular form in this section. Because of the great quantities of data involved, only the arithmetic mean values from each series of five tests are presented, along with their standard deviations. Figure 2 below is a stylized thrust-time curve from a staging test; on it are indicated all of the symbolized performance values presented in the tables, except total impulse (I_T), which was obtained by counting the 1mm squares under each curve. Because of the configuration of the recording apparatus, time runs from right to left.

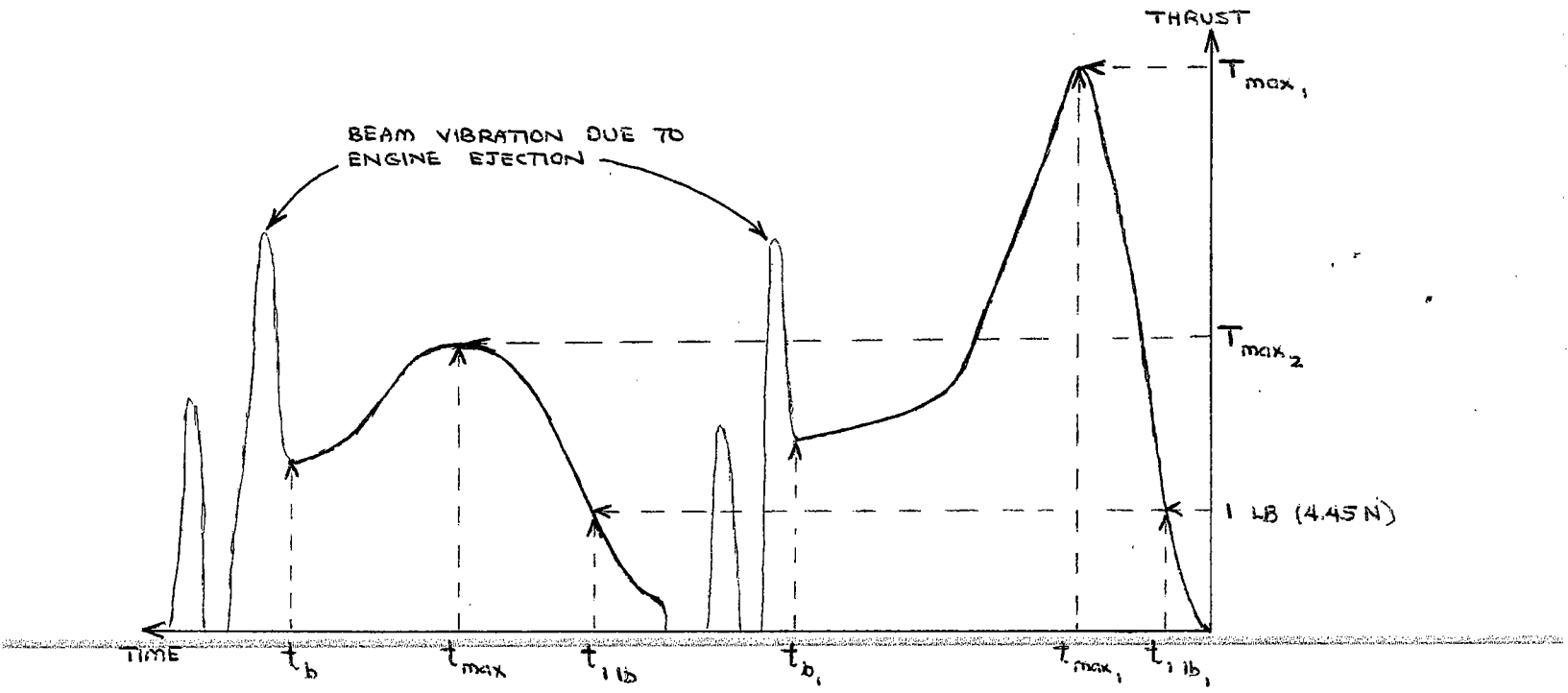


FIGURE 2. Representative thrust-time curve, annotated.

Figures in parentheses in Tables 1-4 below are standard deviations of the performance values immediately above. Each entry is the mean value over five tests.

IGNITER	F_{max}	t_{max}	$t_{1\ lb}$	t_b	I_T
electric match	24.7	0.227	0.061	0.403	4.10
	(1.5)	(.007)	(.006)	(.036)	(.21)
Sure-Shot	21.1	0.205	0.043	0.439	4.23
	(1.7)	(.013)	(.005)	(.037)	(.19)
Estes, tissue wadding	24.1	0.215	0.047	0.424	4.31
	(0.9)	(.008)	(.003)	(.047)	(.19)
plain nichrome, tissue wad.	24.2	0.221	0.053	0.441	4.46
	(1.3)	(.007)	(.005)	(.063)	(.19)
Estes, tape	24.7	0.217	0.050	0.428	4.30
	(0.4)	(.009)	(.004)	(.023)	(.06)
FSI	24.4	0.215	0.040	0.464	4.61
	(1.3)	(.008)	(.004)	(.061)	(.18)
AVI, tissue wadding	26.5	0.215	0.041	0.431	4.74
	(1.5)	(.007)	(.004)	(.030)	(.10)
NORMAL VALUE	24.8	0.219	0.048	0.443	4.42
	(1.4)	(.009)	(.007)	(.045)	(.17)

TABLE 1. Ignition test results for Estes B14-0.

IGNITER	F_{max}	t_{max}	$t_{1\ lb}$	t_b	I_T
AVI, tissue wadding	11.1	0.225	0.097	0.309	1.92
	(0.8)	(.031)	(.002)	(.022)	(.07)
plain nichrome, tissue wad.	10.8	0.216	0.091	0.321	1.97
	(0.8)	(.011)	(.011)	(.024)	(.05)
Estes, tissue wadding	11.1	0.206	0.092	0.319	2.03
	(0.5)	(.001)	(.006)	(.019)	(.07)
Estes, tape	10.9	0.214	0.099	0.329	2.00
	(0.3)	(.012)	(.010)	(.022)	(.07)
Sure-Shot	11.6	0.216	0.094	0.317	2.00
	(0.2)	(.005)	(.003)	(.008)	(.03)
FSI	11.0	0.216	0.097	0.326	1.99
	(0.4)	(.011)	(.006)	(.015)	(.09)
NORMAL VALUE	11.1	0.211	0.093	0.318	1.99
	(0.6)	(.010)	(.008)	(.018)	(.07)

TABLE 2. Ignition test results for Estes A8-0.

CONFIGURATION	t_{max}	t_b	$t_{1\ lb}$	Δt_{max}	Δt_b	Δt_{1lb}	delay	I_{T_2}
from B14, tape collar	0.248 (.016)	0.459 (.048)	0.079 (.002)	0.029	0.016	0.029	0.03	4.28 (.16)
from B14, no collar	0.261 (.017)	0.495 (.049)	0.090 (.015)	0.042	0.052	0.052	0.05	4.37 (.14)
from B14, 3" separation	0.265 (.009)	0.502 (.056)	0.092 (.015)	0.046	0.059	0.044	0.05	4.46 (.15)
from B14, tandem	0.249 (.008)	0.550 (.085)	--- ---	0.030	0.107	---	0.03?	5.70 (.06)
from A8, 3" separation	0.270 (.006)	0.512 (.042)	0.095 (.009)	0.051	0.069	0.047	0.06	4.55 (.11)

TABLE 3. Staging delays for Estes B14-0 as upper stage engine.

CONFIGURATION	t_{max}	t_b	$t_{1\ lb}$	Δt_{max}	Δt_b	Δt_{1lb}	delay	I_{T_2}
from B14, tape collar	0.335 (.009)	0.451 (.014)	0.219 (.008)	0.124	0.133	0.126	0.13	2.02 (.05)
from B14, no collar	0.338 (.008)	0.445 (.016)	0.224 (.010)	0.127	0.127	0.131	0.13	2.00 (.03)
from B14, 3" separation	0.359 (.009)	0.438 (.014)	0.232 (.013)	0.148	0.120	0.135	0.13	1.96 (.04)
from B14, tandem	0.285 (.018)	0.400 (.016)	0.170 (.015)	0.074	0.074	0.073	0.07	2.53 (.08)
from A8, tape collar	0.335 (.005)	0.444 (.008)	0.218 (.007)	0.124	0.126	0.121	0.12	2.11 (.04)
from A8, no collar	0.334 (.021)	0.435 (.007)	0.219 (.011)	0.123	0.117	0.126	0.12	2.08 (.06)
from A8, tandem	0.260 (.006)	0.339 (.007)	0.114 (.004)	0.044	0.021	0.021	0.03	2.95 (.02)

TABLE 4. Staging delays for Estes A8-0 as upper stage engine.

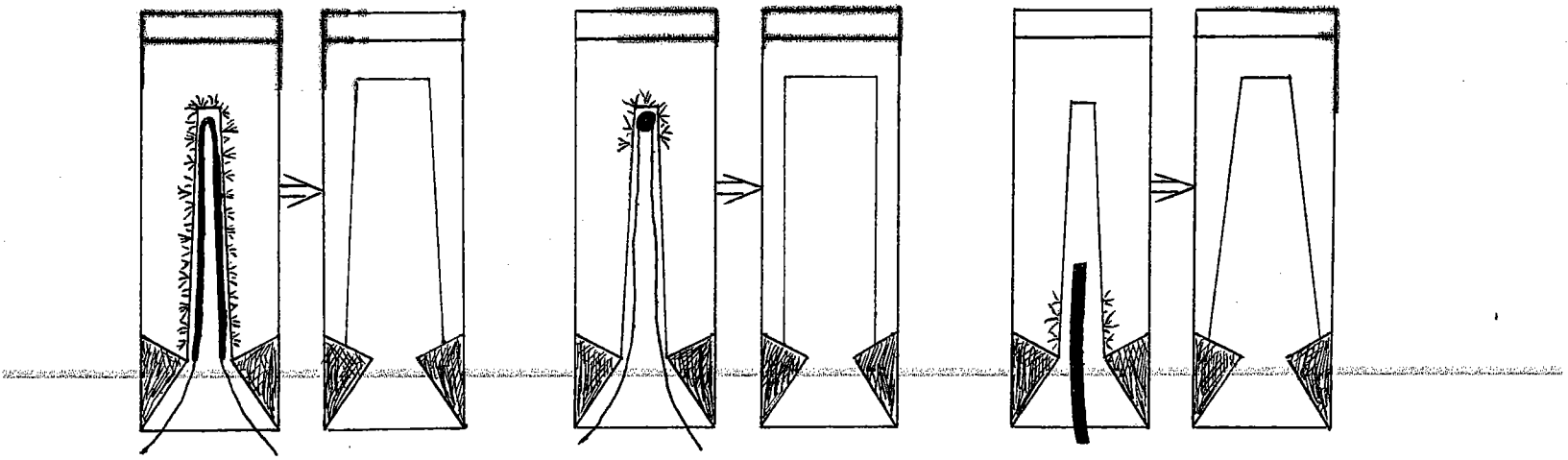
ANALYSIS OF DATA

In order to properly analyze the data from this project, it was first necessary to decide which of the many possible ballistic characteristics of the rocket engines were likely to be affected by the ignition and staging techniques being tested. For the ignition tests, it was felt that different igniters could possibly have different degrees of success in lighting the entire surface of propellant grains, leading to differences in burning surface area (and thus peak thrust, chamber pressure, and burning time). Chamber pressure and burning surface area are not directly measurable, but peak thrust is and they may be inferred from it. An indication of burning rate and thrust buildup rate was obtained by measuring the time from ignition (defined here as the point where thrust reached 3% of its eventual peak value) to three critical points on the thrust curve: the point where the thrust reached one pound (4.45 Newtons), the point of peak thrust, and the point where the grain burned through and the engine was ejected from the thrust stand. A comparison of the time required to reach these three points for different igniters should be a good indicator of their effectiveness.

In order to establish a "normal" value for buildup time and peak thrust for later use in the staging tests, an arithmetic mean was taken for each of these values over all test data, excluding those from the few tests where there was a significant ignition-dependent effect. In all measurements of thrust and computations of impulse, due allowances were made for propellant weight loss effects and the non-zere starting point of some of the recorder traces.

The ignition tests on cored-end-burning type engines (the Estes A8-0) indicated that their performance is independent of the ignition system used; their grain surface area was so small that virtually any igniter could light it all at one time. See Table 2. The results for cored type engines (the Estes B14-0), however, showed some variation between igniters, as discussed below.

Conventional nichrome igniters are designed to ignite the whole grain surface simultaneously; plain wire heats evenly along its whole length, and Estes igniters have a low-flash-point coating along all of the portion which goes inside the engine. A burning solid propellant regresses paralell to its ignited surface, so if a cored engine is ignited evenly all over its core surface, then the core will maintain its geometrical shape as it expands during combustion. See Figure 3A below. X-rays have indicated that the initial shape of a B14's core is the frustum of a cone; an igniter which ignites the core surface evenly will cause this shape to expand but not change shape. An igniter which lights the narrow part first will cause the core to develop into a cylinder (see Figure 3B), which has more burning



3A: Estes igniter 3B: AVI igniter 3C: Sure-Shot igniter

Figure 3. Burning surface development for B14 cored engines.

surface than the frustum of a cone having the same base diameter. Combustion gases escaping from the point first ignited complete the ignition of the core surface in this case, but it takes some time for these gases to be generated and reach the bottom of the core, so the top of the grain "gets ahead" of the bottom by a distance equal to the burning rate times the delay time. This changes the initial shape. $F = \rho A_b \dot{r} v_e$, so increasing burning area A_b will increase thrust, both directly and by increasing chamber pressure, which leads to increases in $\dot{r}$ and v_e.

The test data indicate that the AVI igniters produced approximately a 10% greater peak thrust than most other types. It is believed that this was due to the fact that their low-flash coating is applied in only a single bead. This means that the igniter will probably light a cored engine only at the point where this bead is located (the narrow end of the tapered core) before being expelled by combustion gases. As explained above, this will lead to the generation of a cylindrical burning surface and higher thrust. For a constant nozzle size, this in turn leads to higher chamber pressure, which leads to higher specific impulse (for black powder), giving higher total impulse. The test data show that this igniter in fact produced the highest total impulse.

If an igniter which lights the narrow end of a cored propellant grain leads to higher thrusts, then it is to be expected that devices which ignite the wide (bottom) portion first will cause lower peak thrusts by accentuating the initial conical shape. See Figure 3C. A fuse-type igniter such as the Sure-Shot will obviously do this, as will an electric match, which sits outside the nozzle and directs a small jet of hot gas into it. This behavior was inhibited in the FSI

fuse igniter by the piece of tissue which was used to hold it into the nozzle. It was observed that the Sure-Shot igniter produced a peak thrust significantly lower than the average value in wire-igniter tests. It may have produced a lower I_T as well, but this cannot be proved conclusively from the data. The electric match produced a total impulse significantly lower than average, indicating a lower average chamber pressure. Peak thrust data, however, did not conclusively indicate degradation there. Because of the slowness of gas-to-solid energy transfer as opposed to solid-to-solid, electric matches were a small amount (approximately .01 sec) slower than wire and fuse igniters in completing ignition and producing peak thrust after initial ignition.

In the tests of staged engines, no method of staging seemed to lead to a significantly faster or slower ignition of the second engine (within the accuracy of the measurements), nor did any method have any significant effect on the peak thrust or delivered I_T of the second engine. The t=0 reference point from which $t_{1\ lb}$, t_{max}, and t_b were measured for the second-stage engine was the point at which the first engine ceased thrusting, burned through its grain, and set the thrust stand vibrating by ejecting itself. The use of this arbitrary reference point will not necessarily produce time values directly comparable to those from single engine tests; the important point is that, if used consistently on all staging tests, it will produce values by which different staging methods may be compared among themselves. Despite these reservations, however, it was necessary to compare the three time parameters for second-stage engines with their "normal" values from single-engine igniter tests of the same engine in order to compute the factor called "delay". "Delay" is defined as

the average difference between the three time parameters for the second engine of a staged pair and the "normal" values for the same parameters.

With the exception of tandeming, all staging methods produced a delay of approximately 0.05 seconds when the upper engine was a B14, regardless of whether the lower engine was an A8 or a B14. See Table 3. These two booster engines have chamber pressures different by a factor of 3 at the point when they burn through their grains, so the force with which the lower engine gases and burning particles are expelled upwards does not seem to be a factor in the delay. Tests done with A8 upper engines showed that, again with the exception of tandeming, all staging methods produced a delay of approximately 0.13 sec. As indicated in Table 4, this was for both A8 and B14 lower engines. Apparently, the transmission of igniting material from lower engine to upper is virtually instantaneous, and is not affected by small distances or the slight increase in pressurization provided by a tape collar. The significant factor seems to be the size of the upper engine nozzle; that of the B14 is 0.17" in diameter, giving it twice the area of the A8's 0.12" nozzle throat. The B14 nozzle would thus permit entry of a larger volume of gases and particles than the A8, containing a greater amount of energy to permit more rapid initiation of the upper engine combustion process.

The tests of tandem engines showed that there was a delay of very approximately 0.03 seconds for a B14-to-B14 combination, and for an A8-to-A8, and 0.07 seconds for B14-to-A8. The dynamics of tandem engines are quite complex; there is a sharp thrust spike at the end of the first engine's burn, indicating a burnthrough of the grain and simultaneous combustion of its remaining slivers of propellant. The burn time, thrust, and total impulse of the second engine are

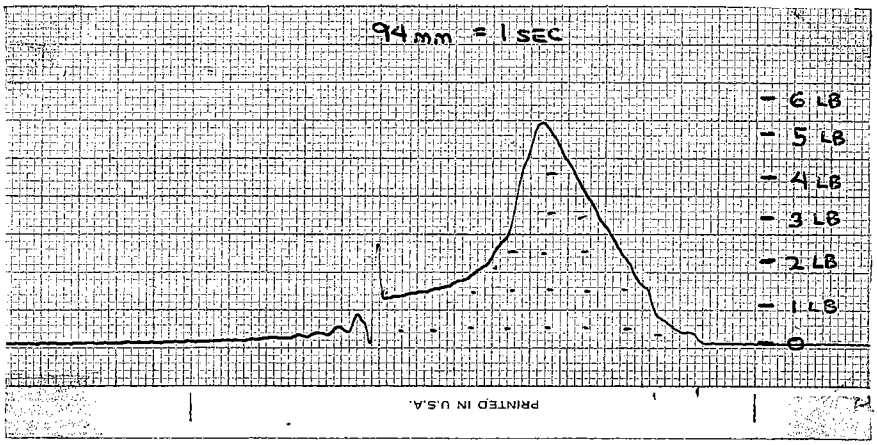
significantly affected by its firing through a second casing and nozzle, so that the validity of the measured "delay" time is somewhat questionable. In tandem tests, the t=0 point for the second engine was taken as the beginning of the rise in the first engine's end-of-burn thrust spike, as it is believed that this represents the point where this engine would have kicked off had it been staged. A full discussion of these phenomena was covered in another project.

CONCLUSIONS

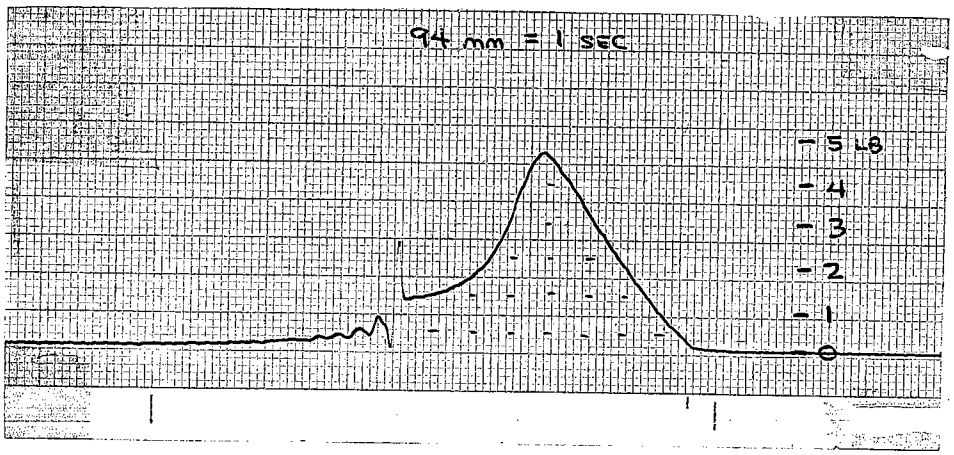
This research project has defined parameters for measuring the effects of using different types of igniters on the subsequent ballistic performance of the two major classes of 18mm black powder model rocket engines, and has reached conclusions concerning these effects. Of particular interest is the fact that the choice of igniter has no effect on the subsequent performance of cored-end-burning type engines, but can affect cored engines to a small degree. This project has additionally defined and measured the delay time between the burnout and separation of lower-stage model rocket engines and the ignition of their upper-stage engines, for all commonly used staging techniques. Of particular interest here is the fact that the technique used has no significant effect, only the choice of the upper engine.

APPENDIX I

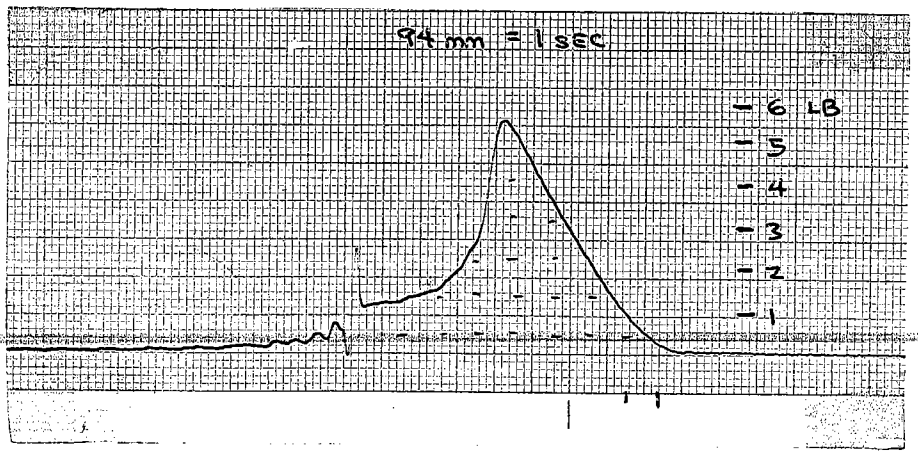
REPRESENTATIVE THRUST-TIME CURVES



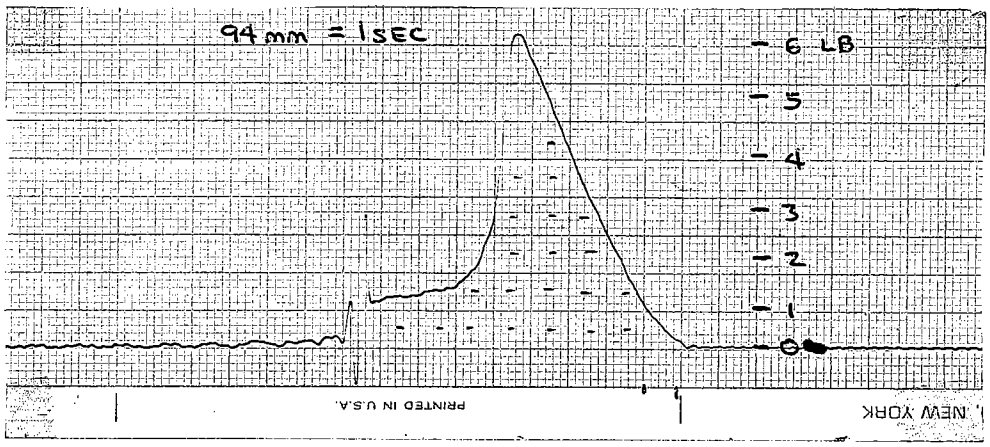
GRAPH 1. B14, ignited by Estes igniter with tissue wadding.



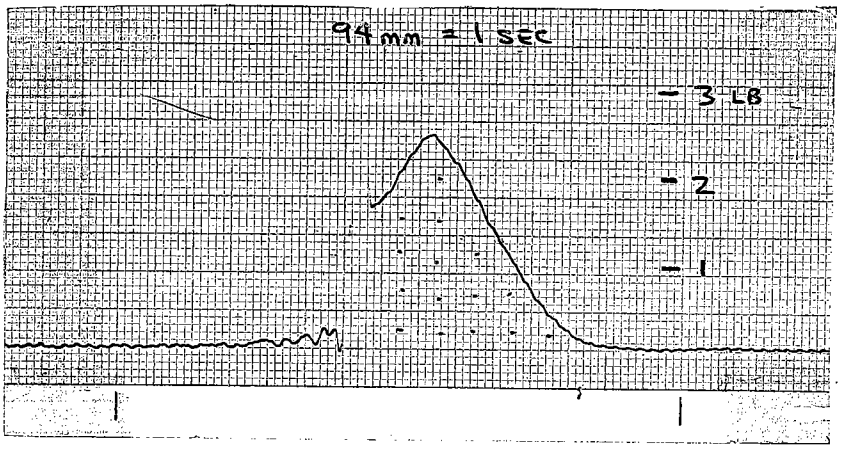
GRAPH 2. B14, ignited by Centuri Sure-Shot.



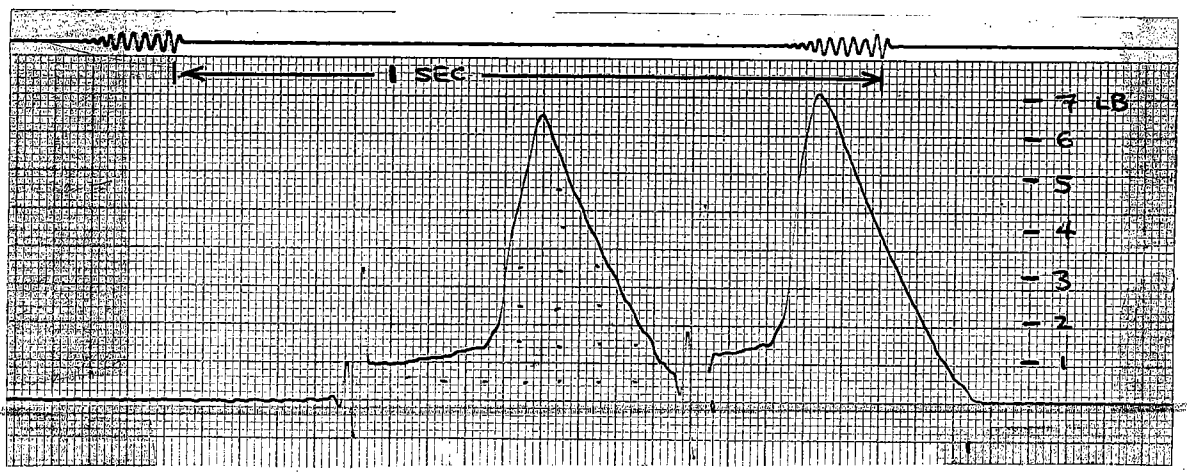
GRAPH 3. B14, ignited by electric match.



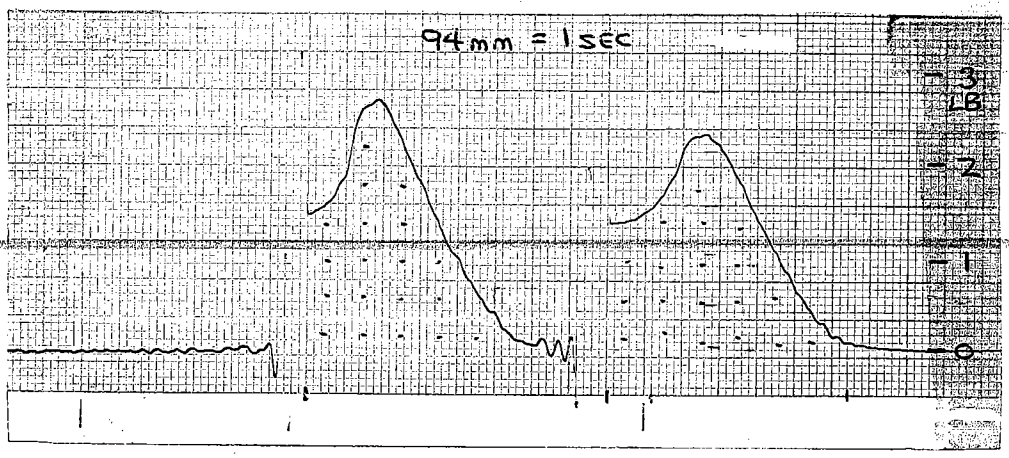
GRAPH 4. B14, ignited by AVI igniter with tissue wadding.



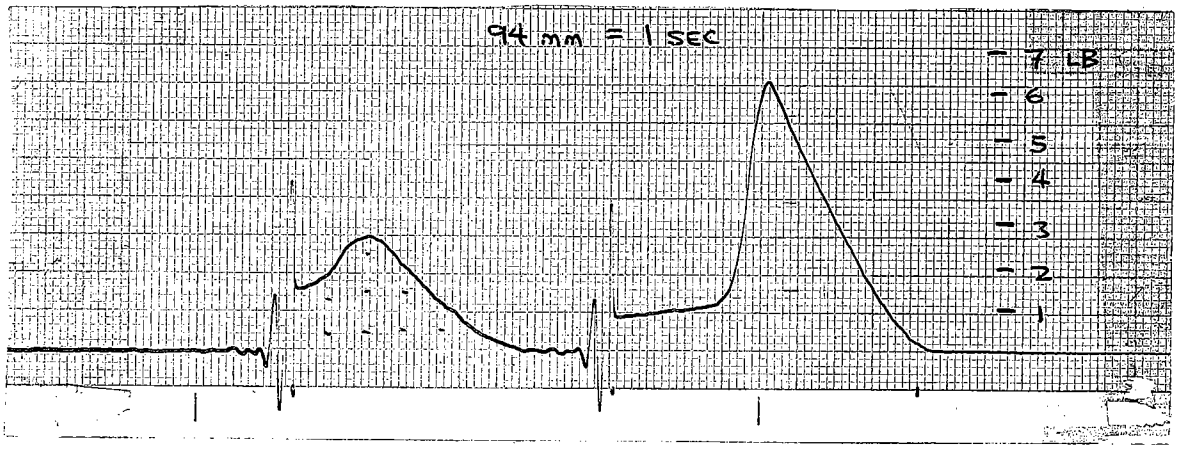
GRAPH 5. A8, ignited by Estes igniter with tissue wadding.



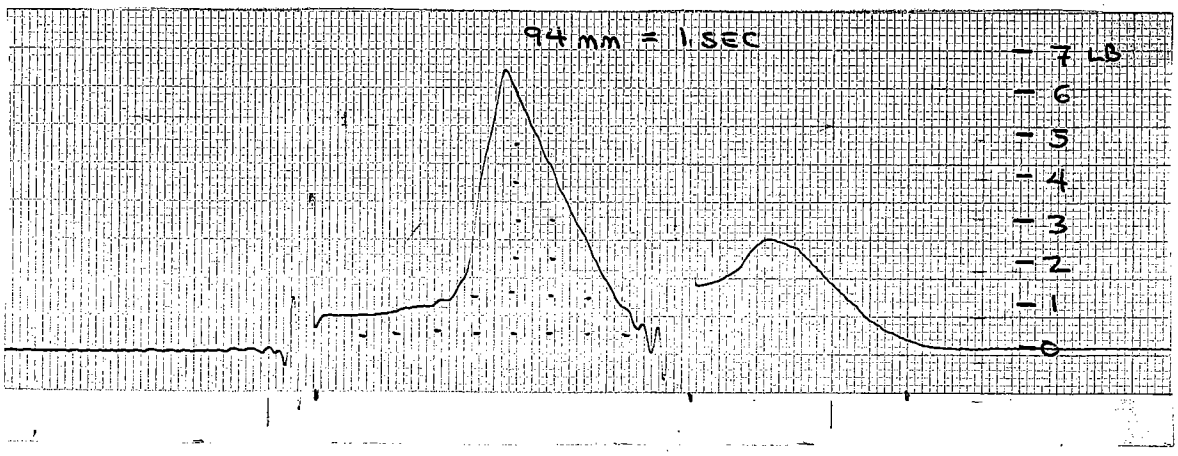
GRAPH 6. B14-B14 staged, adjacent with tape collar.



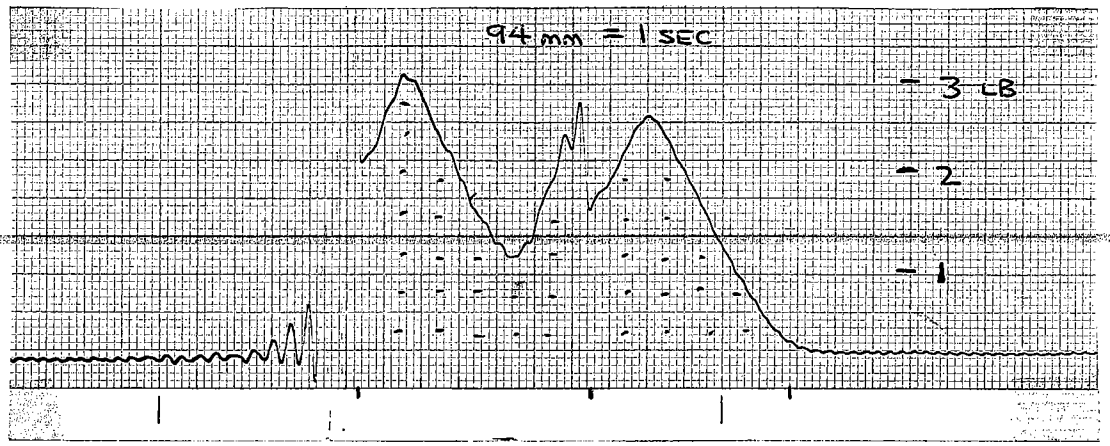
GRAPH 7. A8-A8 staged, adjacent without tape collar.



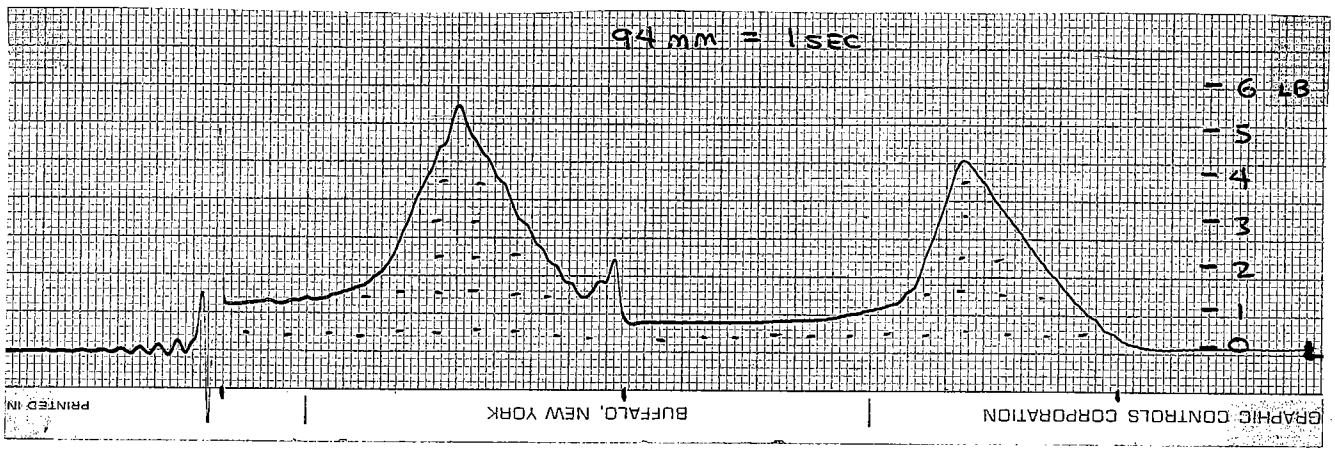
GRAPH 8. B14-A8 staged, adjacent without tape collar.



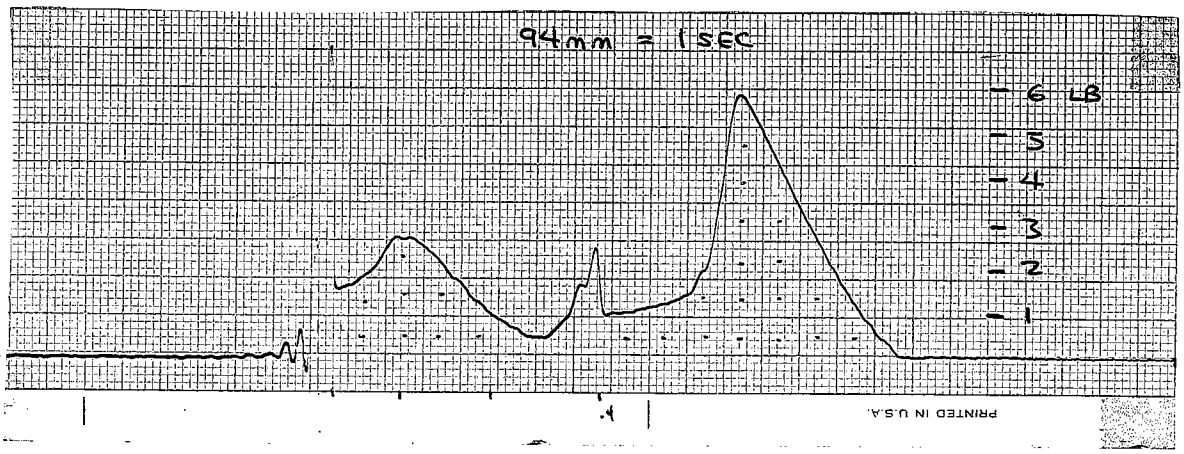
GRAPH 9. A8-B14 staged, 3" separation.



GRAPH 10. A8-A8 tandem.



GRAPH 11. B14-B14 tandem.



GRAPH 12. B14-A8 tandem.